# Technology Roadmap
*for*
# Materials of Construction, Operation and Maintenance in the Chemical Process Industries

MATERIALS TECHNOLOGY INSTITUTE
OF THE CHEMICAL PROCESS INDUSTRIES, INC.

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D.C. Agarwal
Krupp VDM

Abbie Alavi
Westvaco

Peter Angelini
Oak Ridge National Laboratory

J.J. (Sean) Barnes
DuPont Company

Homi C. Bhedwar
DuPont Company

Pat Burke
Materials Technology Institute

Howard Chiang
Equistar

Phil Craig
DuPont Lanxides Composites

Sheldon W. Dean, Jr.
Air Products & Chemicals, Inc.

B. J. Fitzgerald
Exxon Chemical Company

Thomas W. Gibbs
Materials Technology Institute

Galen Hodge
Haynes International

A.S. Krisher
Materials Technology Institute

Eugene L. Liening
Dow Chemical Company

James M. Macki
Materials Technology Institute

B.J. Moniz
DuPont Company

Tony Nemzer
FMC

David W. Richerson
Industry Consultant

Sandy Sharp
Westvaco

Robert Smallwood
Cytec Industries

Merrill Smith
U.S. Department of Energy

Charlie Sorrell
U.S. Department of Energy

Dan Steinmeyer
Industry Consultant

Paul K. Whitcraft
Rolled Alloys

Joseph Zoeller
Eastman Chemical Company

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# Executive Summary

The chemical industry has prepared a vision of how it will meet its competitive challenges through the year 2020. *Technology Vision 2020: The U.S. Chemical Industry* is a call for "action, innovation, and change" and describes "the state of industry, a vision for tomorrow, and the technical advances needed to make this vision a reality." As part of its strategy for achieving future goals, the chemical industry is working to develop technology roadmaps for many important research areas.

Materials technology is one of the many areas targeted by the chemical industry for technology roadmapping activities. Materials play a critical role in the economic performance and growth of the chemical process industries, and new materials technology will be an essential part of the industry's strategy for achieving its vision. Many of these advances directly relate to materials for the construction of process equipment used in the chemical processing industry, as well as materials performance in the operation and maintenance of chemical processes.

The industry began to define its needs in materials research through a workshop held in May 1998. The workshop was organized by the Materials Technology Institute of the Chemical Process Industries, Inc., in cooperation with the U.S. Department of Energy, to facilitate the development of a technology roadmap for materials of construction, operation and maintenance. Attendees included participants from the materials R&D community, the chemical industry, national laboratories, government, and academia.

The workshop identified performance targets, areas of critical opportunity, barriers to reaching targets, and research needed to overcome key barriers. Performance targets were set for the use of capital and energy, as well as increased asset productivity. A safer operating environment and reduced environmental impacts were also identified as important goals.

High priority opportunities for new materials include materials for high temperature and corrosive environments, and control, prediction and monitoring technology. Materials are needed to withstand high temperatures (1000-3000˚F) while retaining superior properties of strength, ductility, corrosion and wear resistance. Equipment that is resistant to chlorine and other halogens could help to reduce the corrosion problems encountered in dealing with these materials. Refractories are another high priority area with potential impacts in many industries where furnaces are used in the manufacturing process. Another important opportunity area with widespread impacts is the prediction and monitoring of materials performance during operation.

**Performance Targets for 2020**

***Reduce capital cost and energy consumption by 30% by 2020***

***Increase asset productivity by***
- increasing uptime 25% by 2020
- improving first pass first quality yield by 20% by 2020

***Provide a safe operating environment with zero on-the-job injuries***

***Protect the environment by:***
- containing the process with zero fugitive emissions
- eliminating toxic discharges to the ground by 2020
- reducing hazardous wastes 50% by 2020

**High Priority Opportunities**

- Metals with high temperature/corrosion capabilities (strong, ductile, corrosion and wear resistant)
- Materials for halogen-based processes (fluorine, chlorine)
- High temperature refractory coatings/materials
- Avoidance of fouling in heat exchangers
- Better corrosion-resistant thermal spray coatings
- Prediction of materials performance without empirical tests
- Materials that resist metal dusting
- Materials for high pressure environments - 10,000 bar
- Self-sensing systems for fitness of service

A number of key barriers were identified that currently inhibit the optimum use of materials in construction, operations and maintenance. The current poor understanding of materials behavior and properties during processing (e.g., alloying, fabrication) or in operating environments is a key barrier. Closely related is the limited ability to model the way materials interact and/or degrade in the process environment, particularly advanced materials. Other key issues include the limited use of life cycle analysis in considering the adoption of new materials, and limitations related to currently available monitoring and control technology.

**Key Barriers to Higher Performing Materials of Construction, Operation and Maintenance**

- Limited ability to model materials interactions
- Lack of fundamental understanding of materials
- Limited understanding of degradation in new materials
- Limits on manufacturability/size and shape
- Lack of support/user participation in development of codes and standards for new materials
- Inability to apply life cycle costs on a consistent basis, incorporating the role of materials
- Lack of reliable, cost-effective, on-line self-sensing methods
- Lack of inexpensive strong, corrosion-resistant material with low life cycle costs
- Scarce research dollars
- Risk involved with using new materials

Priority research needs are diverse, but emphasize overcoming the key barriers to the development and use of better materials of construction, as well as improving performance in operations and maintenance. The development and design of innovative new materials that have high performance capabilities for severe environments is a top priority.

Other critical research areas include acquisition of fundamental knowledge of materials and materials behavior, better control and inspection techniques, improved prediction and design capability, and better joining and fabrication techniques. Development of codes, standards, and specifications for new materials is an overarching requirement, as is the need to provide better transfer of information on materials to end-users and equipment developers.

**Priority Research Needs**

- Alternate alloy systems for high temperatures
- Longer life refractories that are field repairable and ductile
- Cost-effective techniques for covering steel with corrosion-resistant alloys
- Chemical-process-resistant carbon steels
- User facility for acquisition of thermophysical, kinetic and mechanical data
- Study of the metal dusting problem
- Data for materials reliability/performance for ceramics and composites
- Big picture controls/global inspection techniques
- NDE for fracture toughness
- Use prototypes and simulation of operating environments
- Prediction of materials performance without empirical tests
- Modeling/life prediction of high temperature materials
- Joining/fabrication techniques for ceramics/other new materials
- Design inspection/maintenance practices/codes for non-metallics
- Technology centers for “like” processes
- “How to” guides for inspectors, users, designers to optimize the use of materials
- Methods for non-instrusive inspection of heat exchangers and tanks
- Systems to inspect hidden equipment details (e.g., pipe supports)
- Life cycle cost models for process equipment and piping systems
- Uniform specification system model

Through research in high priority areas, progress can be made toward the major goals reflected in this roadmap. For effective resource leveraging, risk minimization, and providing a stable baseline for funding, precompetitive research should be cooperatively supported through the chemical industry, equipment manufacturers, and the Federal government. The development process should be directed by technology end-users.

# 1 Overview

## 1.1 The Chemical Industry Vision for 2020

The chemical industry has prepared a vision of how it will meet its competitive challenges through the year 2020. *Technology Vision 2020: The U.S. Chemical Industry*[1] is a call for "action, innovation, and change" and describes "the state of industry, a vision for tomorrow, and the technical advances needed to make this vision a reality." Major forces for change in the industry include: increased globalization of markets; societal demand for improved environmental performance; the need for increased profitability through capital and asset productivity; higher customer expectations; and changing workforce requirements. Technology research, development and deployment will be vital to meeting these challenges and seizing future opportunities for market growth.

As part of its strategy for achieving future goals, the chemical industry is working to develop technology roadmaps for many important research areas. Technology roadmaps link broadly defined strategic goals in the vision with a detailed research agenda of short-, mid- and long-term R&D activities. They provide a way for decision-makers to make strategically-driven investments in R&D that will increase profitability while achieving goals for improved energy efficiency, safety and environmental performance.

## 1.2 The Role of Materials

Materials technology is one of the many areas targeted by the chemical industry for technology roadmapping activities. Materials play a critical role in the economic performance and growth of the chemical process industries, and new materials technology will be an essential part of the industry's strategy for achieving its vision. Advances in materials technology are discussed throughout *Technology Vision 2020* as important industry needs and challenges. Many of these advances directly relate to materials for the construction of process equipment used in the chemical processing industry, as well as materials performance in the operation and maintenance of chemical processes.

Effective materials selection is vital to the construction and operation of chemical reactors, furnaces, steam generators, heat exchange systems, separation systems, storage vessels, piping systems, and a host of other unit operations in the chemical plant. Materials are critical to effective process control, and greatly impact the cost, longevity, and reliability of equipment. They are also critical from the standpoint of economic competitiveness in the global marketplace.

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[1] *Available from the American Chemical Society, Washington, D.C. or http://www.acs.org.*

Technologies that depend on materials are found throughout the chemical plant. Effective seal, gasket and valve materials are essential for containing and controlling process fluids and emissions to ground, air or water. Materials with unique physical properties are used to make thermocouples, probes, sensors and other devices that monitor and detect process conditions and provide feedback for efficient process control and maintenance of equipment. Coating and insulating materials help to protect equipment from corrosion and erosion, and reduce energy losses. Materials specially designed for high temperature, corrosive environments ensure equipment integrity and reduce the possibility of equipment failure and catastrophic or abrasive deterioration. Materials are very important to the chemical industry -- the way they are used can significantly affect the energy intensity, productivity, cost and environmental performance of the chemical manufacturing process.

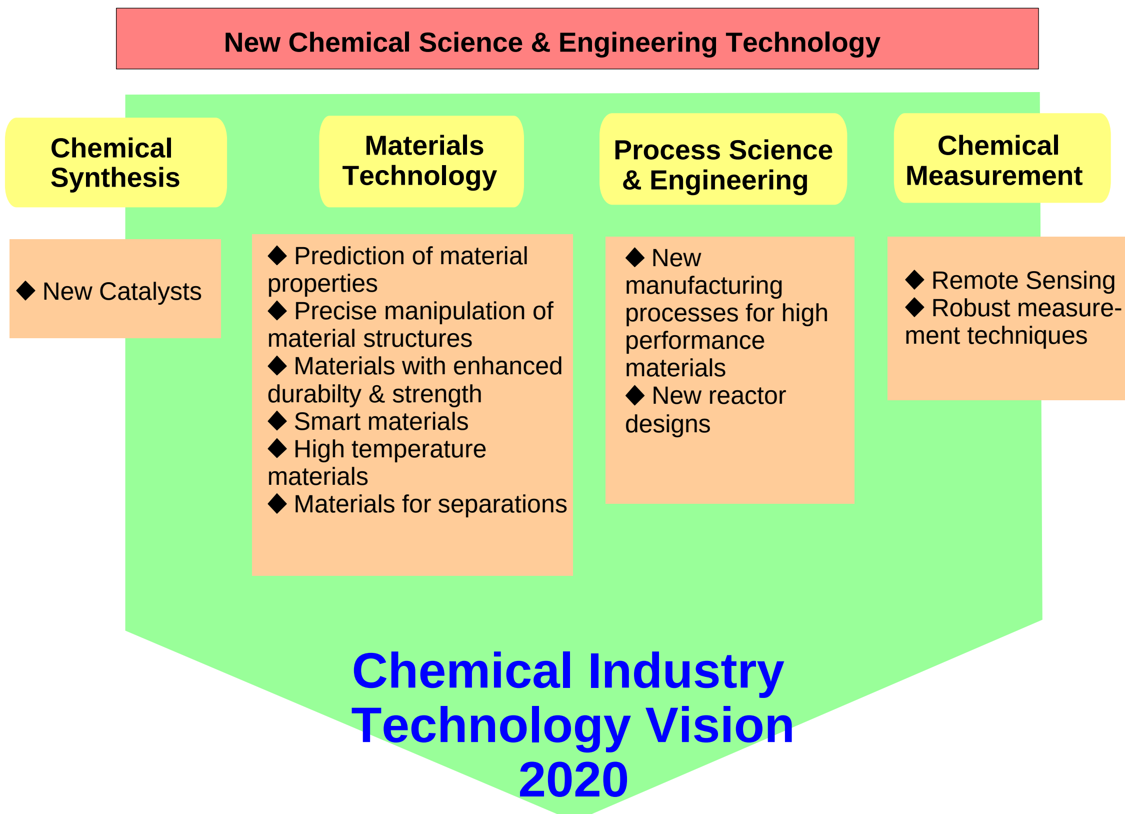


Exhibit 1-2. Materials Needs and Challenges Identified in Vision 2020

Exhibit 1-2 illustrates the vital relationship of materials to the research needs that are identified in the chemical industry vision for the future. The importance of materials development to the chemical process industries must not be understated. Materials in general, and especially materials of construction for process equipment, have been identified as a priority research need in nearly all chemical industry technology roadmap activities to date.

The industry began to define its needs in materials research through a workshop held in May 1998. The workshop was organized by the Materials Technology Institute of the Chemical Process Industries, Inc.[2], in cooperation with the U.S. Department of Energy, to facilitate the development of a technology roadmap for materials of construction, operation and maintenance. Attendees included participants from the materials research and development community, the chemical industry, the national laboratories, government, and academia. The results of this workshop provide the foundation for this technology roadmap.

2 *MTI, founded in 1977, is a not-for-profit technology development organization representing private industry. It sponsors generic, non-proprietary studies conducted on the selection, design, fabrication, testing, inspection, and performance of materials of construction used in chemical processing. MTI members include companies from the chemical processing, refining, and equipment manufacturing industries.*

# 2 Trends in Materials Selection

## 2.1 Advances in Materials

The development of new materials has helped to fuel the growth of the chemical industry and has changed society dramatically during this century. Traditional materials such as wood, glass, metals, and natural fibers have been replaced in some cases with synthetic materials such as polymers and composites. These new materials perform better and provide increased flexibility in design and manufacturing.

Advances in the development of composite materials (e.g., mixtures of polymers and fibers, of metals and ceramics) have greatly extended the range of performance and potential applications for these new materials. Blends of polymers and other materials have resulted in new materials with better performance than single-polymer systems. Research has helped to increase the functionality of existing materials and improve their performance. The advent of “smart” materials (e.g., electrochromics, controlled-release devices, shape memory alloys) brings the ability for materials to self-repair, actuate and transduce.

There has been an explosion in technologies that modify the surfaces of materials. New coating technologies, films, self-assembly or reactive approaches are being developed to create materials with improved performance and unique properties. There are so many of these new surface modification techniques that it has been difficult to focus their attributes on broader ranges of applicability in the industry. Such technologies have great potential to increase the efficiency of chemical processes and reduce the costs of operating and maintaining equipment.

The cost of developing and incorporating advanced materials, however, is high. The reliability of new materials is unproven in most practical applications, and exploring their use in a process environment is risky. Significant R&D, from bench scale experiments to the construction and testing of prototypes, is usually necessary before a new material can be implemented in chemical processing equipment. Fabricability into cost-effective forms is often a significant barrier to the use of newly developed materials. In many cases, the expense and risk attached to new materials R&D puts it low on the corporate research priority list.

In spite of the risk, research into new materials is pursued by a number of companies, primarily for specific product applications. In the Federal sector, the U.S. Department of Defense supports a relatively large materials research program primarily focused on defense applications, although much of this research could be useful in industrial applications. The U.S. Department of Energy supports a diverse materials research program (Office of Energy Research, Office of Fossil Energy, and Office of Energy Efficiency and Renewable Energy/Office of Industrial Technologies) through universities, industry research institutes, and the national laboratories (Oak Ridge National Laboratory, Los Alamos National

Laboratory, Sandia National Laboratory, and others). The research supported by the U.S. Department of Energy emphasizes the development of innovative new materials that improve the energy efficiency and environmental performance of industrial processes.

## 2.2 The Materials Selection Process

When selecting construction materials it is essential to know how the materials will behave when exposed to the actual operating environment. This may be done partly by modeling, although empirical modes are generally more reliable. In particular, special attention must be given to the following factors: potential for corrosion, operating temperatures and pressures, unexpected operating conditions, and start-up and shut-down procedures. A large share of equipment operation and maintenance costs in the chemical processing industries are the result of materials failure due to abrasive, corrosive or high temperature environments.

Corrosion commonly occurs in metals and alloys when they come into contact with chemicals and a usually stable compound is formed at the surface (referred to as the corrosion product). Corrosion in metals can also occur along grain boundaries or other areas of weakness because of weaker resistance to attack or electrolytic action. In most cases corrosion in metals and alloys can be measured through the loss of metal and depth of internal attack. Non-metallic compounds (e.g., plastics and ceramics) fail through deterioration when exposed to certain environments. The deterioration occurs because the compound is susceptible to swelling, crazing, cracking, softening or some other phenomenon that is physiochemical in nature. It is seldom possible to fully evaluate the chemical resistance of non-metallics by simple weight loss. A combination of mechanical and physical techniques must be employed, depending on the type of material.

Many factors can affect the corrosion rate of a material. Corrosion in metals, for example, is greatly affected by the pH of the environment (acidity or alkalinity). Oxidizing agents, such as dissolved air, may accelerate the corrosion of some materials and retard corrosion in others. The rate of corrosion tends to increase with temperature. Corrosive action also generally increases with the velocity of the flowing fluid.

Both very high and very low temperature operations create a challenge for materials selection. Among the most important high temperature properties are creep-rupture, short-time strength, thermal conductivity, thermal expansion, ductility, and stability. In many chemical processes, however, strength and mechanical properties are second in importance to the corrosive nature of the surroundings. Hot oxidizing environments, for example, require materials that are resistant to oxidation (e.g., steel with a high percentage of chromium, nickel-based alloys, or intermetallic alloys). Environments that contain hot halogen gases (chlorine) require costly highly corrosion-resistant alloys such as Alloy 800 and Inconel 600, and in some rare cases platinum-clad nickel-based alloys. Refractories are another class of high temperature material that may have resistance to high-temperature chemical attack. These materials must also resist erosion by gases with entrained fine particles, and abrasion by gases with large particles.

Equipment that operates at very low temperatures (e.g., cryogenic gases) can also create difficulties in materials selection. At low temperatures many metals lose their ductility and impact strength, although yield and tensile strength may increase. The selection of materials for very low temperature applications requires specialized knowledge as well as unique qualification tests to demonstrate adequate toughness of the material at the operating temperature.

General corrosion data as well as physical and mechanical properties data are available for a wide variety of materials (e.g., metals, plastics, glass, brick, rubber, epoxies) in standard engineering handbooks. Similar data for polymers, ceramics and ceramic composites is very limited, as is the understanding of the corrosion behavior of materials. When data is not available, the materials selected must be subjected to corrosion and other tests (e.g., tests for strength, ductility, toughness) that simulate the operating environment and help determine how the material will perform in practice. Experience is also a very strong factor in making reliable decisions.

If corrosion is not an issue, the least expensive material with the appropriate mechanical properties is usually selected. The corrosion resistance of a material can be evaluated by: actual operating experience; small scale testing under commercial or pilot-scale conditions; sample tests in the field; or laboratory tests where the material is exposed to the actual plant liquid or simulated plant environments. The most reliable of these are plant or field tests, which can incorporate process changes/upsets, but these also require the most time to conduct. An increased understanding of the corrosion process often requires all of the above.

Laboratory corrosion tests are frequently the quickest and most easily accomplished means used today for determining preliminary materials selection for equipment. However, it is not yet possible to use laboratory tests to predict the behavior of a material under actual plant operating conditions. The main difficulty lies in interpreting the results of the laboratory test and translating how they relate to plant performance. Tests must be able to determine how a number of elements in the process may affect corrosion (e.g., chemical resistance, dissolved gases, velocity, turbulence, abrasion, crevice conditions, hot-wall or cold-wall effects, trace impurities).

It is often difficult to determine just what the conditions of service are, and then to reproduce them exactly in the laboratory. Chemical processes are further complicated by the fact that the composition and nature of the process fluid may change during the process (e.g., evaporation, distillation, polymerization, sulfonation, etc.). However, preliminary laboratory tests can eliminate certain materials and narrow the range of potential materials of use. Further selection must then be made based on working knowledge, by constructing larger-scale equipment in which the operating environment can be more completely simulated, or by trial and error (the least desirable alternative). In today's competitive environment, many, if not most, projects are schedule driven. There is therefore a need for reliable short-term tests that will aid in materials selection (both metallic and non-metallic).

Corrosion and other factors lead to fouling of equipment and piping systems. Fouling can occur on the process side or the utility side (e.g., cooling water). Fouling is poorly understood and leads to costly equipment shutdown, where equipment must be removed and restored to adequate process capability and energy efficiency.

## 2.3 Standards for Materials of Construction

Consensus standards allow designers and users of materials to expect certain minimums of performance from specific materials, allow the purchase of comparable materials from different suppliers, and capture the best current experiences of the industry. Producers that manufacture materials to accepted standards can also be more confident of a ready market and can produce in large quantities. A number of organizations currently generate standards that may apply to materials of construction, notably the *American National Standards Institute* (ANSI), the *American Society of Mechanical Engineers (*ASME), the *American Society for Testing and Materials* (ASTM), the *National Association of Corrosion Engineers* (NACE), and the *International Organization for Standardization* (ISO). Essentially all these standards apply to common materials of construction (e.g., metals, alloys, plastics, bricks, glass, etc.). Standards for advanced materials (e.g., intermetallic alloys, ceramics, ceramic composites) as applied to construction are limited. Tightening of standard specifications is also needed to get more consistent performance from materials that are currently available.

# 3 Performance Targets

Optimum use of materials can contribute directly to many of the goals stated in the chemical industry vision. Specifically, efficient selection of materials could promote

- Optimization of existing processes to improve energy efficiency;
- Efficient design of new processes;
- Improvements in health, safety, and environment; and
- Reduction in the cost of process operation.

Performance targets for materials of construction, operations and maintenance, shown in see Exhibit 3-1, illustrate the far-reaching impacts of materials on chemical processing. Optimizing the use of materials has the potential to improve the safety of the operating environment in chemical plants by increasing the reliability of equipment and reducing or eliminating equipment failures. Safer equipment and processes means fewer on-the-job injuries and accidents. Using better materials can also lengthen the interval between scheduled plant shut-downs and reduce the incidence of emergency shut-downs — providing greater productivity and profit margins. Specific goals are set to increase asset productivity by increasing uptime (the percentage of time the plant is making first quality product) by 25 percent and

### Exhibit 3-1. Performance Targets for Materials of Construction, Operation and Maintenance

***Reduce capital cost and energy consumption by 30% by 2020***

***Increase asset productivity by***
- increasing uptime 25% by 2020
- improving first pass first quality yield by 20% by 2020

***Provide a safe operating environment with zero on-the-job injuries***

***Protect the environment by:***
- containing the process with zero fugitive emissions
- eliminating toxic discharges to the ground by 2020
- reducing hazardous wastes 50% by 2020

improving first pass, first quality yield by 20 percent. Better yields can be obtained through use of materials for reactors, separation equipment, and heat exchangers that can better withstand higher temperatures or corrosive environments. New materials that can be used to design more effective sensors can also contribute to higher yields through better, more accurate process controls.

Using materials that are optimally suited to their application could help to lower capital costs by reducing the amount of over-sizing and over-design that is currently inherent in much of the equipment in use today (assuming these materials are cost-competitive with current materials). More effective use of materials and better designed equipment will also lower energy consumption and the associated operating costs. Specific goals are set to reduce capital cost and energy consumption by 30 percent through the use of optimized materials in equipment and plant construction, operation and maintenance.

Environmental performance is considerably impacted by the wise use of materials in chemical processing facilities. New materials can be used to reduce fugitive emissions of volatile compounds to the environment, some which are hazardous or toxic in high concentrations.[3] New materials coupled with more effective joint design can help to reduce discharges of hazardous and toxic waste. Specific goals are set to lessen the environmental impacts of chemical production through better use of materials. These include zero fugitive emissions, the elimination of toxic discharges to the ground, and a reduction in hazardous waste generation by 50 percent by 2020.

Broad targets for the U.S. chemical industry that can be greatly impacted by advances in materials are illustrated in Exhibit 3-2. These focus on the economic preservation and growth of the industry in general, as well as increases in U.S. jobs and export markets. An important goal is to analyze and minimize complete life cycle costs in determining process economics. Complete life cycle analysis would incorporate the embodied costs in materials used in the construction of equipment as well as all associated maintenance costs.

### Exhibit 3-2. Broad Targets for the Industry

***Preserve and enhance U.S. chemical industry economic leadership***

- technical jobs
- technical leadership

***Optimize process economics***

- achieve lowest life cycle costs (lowest combined capital, energy, maintenance and downtime costs)

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[3] *Fugitive emissions arise when small amounts of volatile compounds leak from valves, seals, pumps, vents and other sources during chemical processing.*

# 4 Materials of Construction

## 4.1 Customer Needs and Opportunities for Materials of Construction

New and improved materials of construction are needed for a wide range of applications (see Exhibit 4-1). The most important of these are high temperature and corrosive environments, monitoring and prediction of material performance, and new or improved materials with unique properties.

*High Temperature and Corrosive Environments*
Materials are needed to withstand high temperatures (1000-3000$^{o}$F) while retaining superior properties of strength, ductility, corrosion and wear resistance. One of the greatest causes of equipment failure in the chemical process industry (CPI) is damage due to corrosion and high temperatures. Materials with enhanced resistance to organic acid environments could improve plant operations and maintenance requirements. Improved materials for chlorine based processes are another high opportunity area. Equipment that is more resistant to chlorine and other halogens would reduce the cost of many of the current corrosion problems encountered in dealing with these materials. Refractories and refractory coatings for high temperature furnaces is a critical opportunity area where new materials could have a significant impact on energy and maintenance costs. Development of high temperature non-stick surfaces could potentially improve maintenance of chemical process equipment. Most available non-stick coatings degrade or become volatile at high temperatures, limiting their usefulness in high temperature conditions.

*Control/Monitoring/Prediction*
The ability to predict material performance in complex chemical systems without empirical tests is a high priority. Conventional testing is frequently invasive and can sometimes require an entire shutdown of the plant or process. For example, monitoring and control of corrosion at high temperatures could substantially decrease the incidence of equipment failure by predicting when preventive maintenance should be performed. The ability to monitor and avoid fouling in heat exchange systems is an important opportunity that could have widespread impacts throughout the CPI.

Predicting the performance of polymers represents an opportunity to help institutionalize the use of polymers as materials of construction. Reliable short-term tests for polymers and systematic failure analysis methods are needed for all classes of polymers. Practical tests are also needed to measure permeation (or non-permeation) through polymer materials.

*New and Improved Materials*
Materials for high and low temperature separations are high on the list of opportunities for new and improved materials. Significant opportunities also exist for specialty alloys, more economic alloys for containment of high pressure environments, and materials for waste heat recovery equipment. Increased recovery of waste heat represents a substantial opportunity to reduce energy consumption and production

costs. Other new material opportunities exist for improved thermal insulation, more effective metal claddings and coatings, and better metal castings. Cast metals are often inferior to their wrought counterparts in terms of toughness.

## Exhibit 4-1. Industry Opportunities and Customer Requirements For Materials of Construction

(◆ = Most Critical Problem Areas/Barriers)

| High Temperature Applications+ 1000° F | New and Improved Materials | Corrosive Environments | Control/Monitoring/ Prediction |
|---|---|---|---|
| Materials to resist metal dusting ◆◆◆ | Low cost, very efficient membranes with unique properties ◆ | Materials with high temperature/ corrosion capabilities ◆◆◆◆◆◆ | Prediction of material performance in complex chemical systems without empirical tests ◆◆◆ |
| High temperature (join-able materials) ◆◆◆ | Specialty alloys/ materials in wider product forms ◆ | Materials for halogen based processes ◆◆◆<br>- fluorine/chlorine◆ | Avoidance of fouling in heat exchange systems ◆◆ |
| High temperature refractory coatings/ refractory materials ◆◆ | Materials for high pressure environments 10,000 bar ◆ | Lower cost materials for corrosive applications ◆ | Monitor corrosion inside piping and equipment at high temperatures ◆ |
| High temperature non-stick surfaces ◆◆ | Materials for waste heat recovery systems ◆ | Materials with wear resistance and liquid corrosion resistance ◆ | Practical test for permeation through polymers ◆<br>– polymers with no permeation |
| High temperature materials - 3000° F strong, ductile, corrosion /wear resistant ◆ | New separation materials - high/low temperature applications | Heat exchange tubing with better corrosion resistance | Better, cost-effective, easier-to-use corrosion control methods |
| Materials for radiant coil - ethylene furnace ◆ | Better thermal insulating materials | Lower cost, easier-to-work-with materials that resist stress corrosion cracking | Sensors for in-line control |
| Reliable anti-coking materials | Optimized metal claddings and coatings | Low cost ways to remove or neutralize chlorides | Systematic failure analysis for polymers |
| High temperature materials application | Reduced catalyst poisoning | Reclamation/de-contamination of process wastes | Quick, reliable laboratory tests for susceptibility to crevice corrosion |
| Materials that allow operation with uncooled walls | Alternatives to asphalt (e.g., biomass, nontoxics) | | Increased reliability of electric resistance welded tubular products |
| Alternate refractories/ductile refractories | Materials for die plates | | 3-D flue gas flow model in the fire box |
| Metals with improved high temperature fatigue resistance | Higher strength versions of common MOCs | | |

## 4.2 Technical and Non-Technical Barriers to the Use of Better Materials of Construction

The key barriers to achieving the performance targets for materials of construction are shown in Exhibit 4-2. Barriers are both technical and non-technical, and range from limited information systems to a lack of fundamental knowledge in materials science.

*Basic Science and Knowledge*

The lack of a fundamental understanding of materials (with respect to corrosion and alloying) is one of the most critical barriers to the advancement of many new materials. Many of the basic mechanisms of materials processing or surface modification are poorly understood and cannot effectively be modeled or predicted. There is also limited information on the degradation of new materials, which can lead to poor prediction of failure situations in plant equipment. Another high priority barrier is the limited understanding among those closest to the actual problems of how to incorporate life cycle costs and the role of materials in the overall cost analysis. Many critical people involved with decisions concerning new materials (e.g., management, scientists, engineers) are not yet fully aware of the impact that materials can have on overall process economics.

There are a number of areas where fundamental understanding of material properties and chemical interactions are not well established. These include, for example, the kinetics of transformation and chemical reactions with materials (aging, phase transformations). Not enough is known about what actually occurs at the surfaces of materials as they are exposed to various operating environments. In general, there is a poor understanding of process conditions, as well as inadequate characterization of practical operating environments, and how they affect materials of construction. One of the reasons for this is the great diversity of chemical processes within the industry and in individual plants.

*Design/Fabrication*

The capability to model the way materials interact within the process is limited. This is the result of insufficient knowledge in basic material science, coupled with poor characterization of the processes and operating environments and how they affect materials. There are also limitations on the fabrication of equipment -- new materials are frequently more difficult to fabricate into the required shapes, and fabrication data usually lags their invention. Consequently, process equipment made from new materials cannot always be produced in the same manner as traditional equipment. It may be more difficult and expensive and is always riskier than producing equipment made from traditional materials. Frequently there is also a lack of qualified fabricators to work with new materials.

In practice, it may be more difficult to use new materials because of uncertain knowledge of long term properties and poorly understood manufacturing and forming processes. Ceramics, for example, have poor (or low) shock resistance compared with other materials — this requires rethinking how ceramics are design and used compared with traditional methods based on metals. Another factor is field repair. Some materials may be difficult to repair at the plant site, or have surfaces that don’t bond well with common adhesives. The inability to incorporate previous practical experience with the material in the initial design – without a history of materials performance – makes the design process more unreliable and risky.

## Exhibit 4-2. Barriers to Development of New Materials of Construction

(◆ = Most Critical Barriers)

| Data Requirements | Design/ Fabrication | Basic Science/ Knowledge | Institutional Issues | Marketing/ Development |
|---|---|---|---|---|
| No centralized database for mechanical properties of materials ◆<br>– creep<br>– thermal physical properties<br>– thermal conductivity | Limited ability to model the way materials interact within a process ◆◆◆◆ | Lack of fundamental understanding of materials ◆◆◆◆◆<br>– corrosion<br>– alloying | Lack of support/user participation in development of codes and standards ◆◆ | Scarce research dollars ◆◆◆ |
| Lack of data on alternate materials | Manufacture-ability/size, shape, application limits ◆◆◆ | Lack of understanding of degradation of new materials ◆◆◆ | Failure to transfer information ◆◆ | Risk involved with using new materials ◆◆ |
| Data not in consistent engineering form | Need to redesign process equip-ment with new materials ◆◆ | Lack of good understanding of life cycle costs and the role of materials ◆◆ | Concerns about intellectual property rights ◆ | Material cost not well integrated with user needs ◆ |
| Proprietary concerns | Lack of qualified fabricators to work with new materials | Too low on the learning curve in materials science research | Materials compatibility information is proprietary | Little collaboration on materials needs ◆ |
| | Inadequate shock resistance of ceramics compared with other materials<br>– thermal expansion | Kinetics of trans-formation and reactions (e.g., aging, phases) | Lack of connection between pure research and user community | Short term investment perspective (ROI vs life cycle) |
| | Poor adhesion of coatings | Permeation problems with coatings | No materials manufacturers in the loop between R&D and end-use | High cost of materials |
| | Lack of field repairability | Lack of fundamental understanding of surfaces | Poor information transfer from old to young | Long payback for new materials |
| | Poor fundamental understanding of how to form materials | Poor characterization of operating environments | Poor information transfer from research community to users<br>– costs<br>– accessible mecha-nisms for information | Long lead development time |
| | Lack of operating experience in materials design | Poor understanding of process conditions | Excessive downsizing in companies | Difficulty in quantifying markets for new materials |
| | Slow to mature joining technology | Solids/composites are more difficult to deal with than liquids/gases | Metals bias/unproven ceramics performance | Lack of materials engineering resources in small companies |
| | Poor understand-ing of reliability engineering | | Materials R&D is not exciting to all management<br>– not a priority until failure occurs<br>– materials is an enabling technology | |
| | | | R&D management style not conducive to materials research | |

*Institutional Issues*

The lack of end-user participation in the development of codes and standards represents a significant barrier to the optimum use of materials. End-users must take a more active role in the development of regulations in order to develop optimum materials use and equipment standardization.

The lack of effective information transfer is a key barrier in the development and use of advanced materials. In general, there is a significant lack of communication and interaction between pure researchers and the materials-user community. Part of the reason for this is concern over intellectual property rights, which inhibits the sharing of information among scientists, industry, and institutions where engineers and scientists work. Another reason is the lack of accessible mechanisms available for transferring information from the research lab to the user.

A real problem is the lack of a materials manufacturer in the loop with the material scientists and end-users. Researchers at the national labs, for example, can generate small amounts of material but can't really address the manufacture of commercial quantities and all the product forms required. Communication between materials researchers and end-users is needed in the early research stages to ensure that the materials developed meet the needs of the industrial user. Another barrier is that materials-compatibility information is frequently viewed as a competitive advantage, allowing companies to differentiate their "commodity" chemical products from those of competitors.

Overall, materials research is not at the top of the corporate research list. Much of the R&D that is conducted is failure-driven — materials are not investigated with any priority until a failure occurs. Materials research also often falls into the category of "enabling" research, which seldom has a clear-cut payoff that can be sold to upper management. Materials manufacturers, on the other hand, generally look for proprietary areas to research so it will be possible to recoup the high costs of development.

*Data Requirements*

The industry currently has no centralized database for mechanical or physical properties of materials for researchers, equipment designers, and specifying engineers to draw upon. Information relating to creep, thermal physical properties, and thermal conductivity of new materials is very difficult to obtain, particularly for new materials. Even when data is available, it is often not in a form that is useable by design engineers.

Another barrier is the lack of materials testing facilities that are broadly accessible. Having access to a testing laboratory would help to defray the risk taken on by individual companies in developing new equipment or processes utilizing advanced materials. These facilities might also serve as a coordinating point for the development of objective material standards.

*Marketing/Development*

Research funding in the materials industry is scarce, which can contribute to a lack of innovation. Overall, many institutions perceive a risk involved with the development and use of new materials. The industry places a large emphasis on product liability because of the legal system, which places an considerable burden on manufacturers. The result is reluctance on the part of industry to attempt to use new materials, even on a pilot scale. The general conservatism for high risk projects goes along with the current short-term investment perspective taken by most companies. New materials may be expensive, require a long lead-time for development, and are associated with long paybacks — all negatives for the large corporate profit-oriented investment strategy. Small companies that might be interested in pursuing development of innovative new materials often lack the resources and skilled researchers to make any real progress beyond the laboratory scale.

Another problem is that the cost of materials is not well-integrated with the needs of the end-users of the equipment. In general there is little collaboration between designers and end-users on optimum material needs such as availability in various product forms. As a result, new materials may cost more than the end-user wants to pay, and the material may fall short of expectations in practical operating environments. As a result, markets for new materials are difficult to quantify. Without realistic expectations for the potential markets, it is difficult to sell the materials development project to R&D management.

## 4.3 Research Needs for Materials of Construction

The research needed to overcome the barriers to new materials of construction are listed in Exhibit 4-3. This Exhibit displays the timeframe for the research and indicates when meaningful results and process improvements can be expected. Symbols are used to indicate top, high and medium priority research. The relative impacts of research on safety, environment, energy, and productivity are also illustrated for the major categories of research.

*Science, Knowledge, and Data Acquisition*

An on-going research program is needed to study the degradation behavior of materials in current operating environments, including the kinetics and initiation/propagation of corrosion and other failure mechanisms. Studying the science of stress corrosion and cracking phenomena is another on-going top priority research need. Both activities would enable progress in reducing equipment failures.

Establishing a user facility for acquisition of thermo-physical, kinetic, and mechanical data would be very helpful to the continued development of new materials. Data collected in the user facility, along with data generated by manufacturers and suppliers of new materials, could contribute to the development of a usable resource for materials reliability and performance. This is a near-term objective that could be met through an extension of existing materials research capabilities in universities and national laboratories. Issues that would need to be addressed include the scope of data (all of industry or just the chemical processing industries) and the question of proprietary data for some materials.

In the mid-term, a high priority is to study the metal dusting phenomenon. Other mid-term efforts should include the application of combinatorial chemistry to ceramics and metals. Successfully developing such techniques could lead to new diagnostic tools and models that could be used in the development of new alloys. Development efforts should include interaction between R&D community, materials companies, and end-users. Long-term efforts should include ways to prevent undesirable secondary phase transformations.

*Control and Inspection*

Better failure analysis of materials in the actual operating environment is a high priority for the near-term. Improved on-line inspection techniques, for example, could significantly reduce catastrophic equipment failures. Characterization of failure mechanisms for polymers and development of failure analysis procedures for high temperature environments are both high priority concerns. Improved inspection methods are also needed to detect flaws in polymers and in glass-reinforced materials. Development of better inspection methods could facilitate the use of some materials (polymers and others) that are currently available but under-utilized as materials of construction.

The development of methods to detect corrosion processes *in situ* is a top priority and could provide results over the next decade. Widely recognized controls and inspection techniques are also needed to help create accepted standards for materials. For example, a long-term effort is needed to develop non-destructive evaluation techniques (NDE) for fracture toughness in new materials.

*Simulation/Design/Prediction*

Process modeling and simulation is a valuable tool for evaluating materials and their applicability to certain processes. Computational process modeling is needed to mathematically determine material behavior under various conditions. For example, studies in computational fluid dynamics and

## Exhibit 4-3. Research Needs For Materials of Construction

(✪ = Top Priority; ● = High Priority; ○ = Medium Priority)
(♧= environment $=productivity ⊛= safety ☼=energy)

| Time Frame | Science/ Knowledge/ Data$☼ | Control/ Inspection ♧♧♧⊛⊛⊛⊛⊛ ⊛⊛⊛ | Simulation/ Design/Prediction♧♧♧♧♧ $$$⊛⊛☼☼☼ | New/ Improved Materials ♧♧$$$$$☼☼☼☼☼☼☼ | Joining/ Fabrication ♧$⊛ |
|---|---|---|---|---|---|
| **NEAR** (0-3 Years) | Establish user facility for acquisition of thermo-physical, kinetic and mechanical data ✪●● | Categorize failure mechanics for polymers ●○<br><br>Develop high temperature failure analysis procedures ○<br><br>Devise inspection methods to detect flaws in polymers and in glass-reinforced materials<br>– e.g. microwave<br><br>Design sensors/ controls to avoid temperature changes (e.g., smart systems) | Conduct studies in computational process modeling ✪✪○○<br>– fluid dynamics, radiant heat transfer<br><br>Develop design methods for brittle materials for chemical processing ○○ | Develop generic coatings to reduce temperature sensitivity ●<br><br>Develop corrosion/erosion resistant ceramics for pumps/seals | Explore joining methods for ODS alloys ✪○<br><br>Conduct R&D on metallic welding processes ○<br><br>Improving existing castings for high temperature materials |
| **MID** (>3-10 Years) | Develop data for materials reliability/performance for ceramics & composites ✪●○<br><br>Study metal dusting phenomenon ●●●●<br><br>Apply combinational chemistry to ceramics and metals ○<br>– potential diagnostic tool/alloy development | Big picture controls and global inspection techniques ✪●○ | Model/predict life of high temp-materials (macro approach) ✪✪○○<br><br>Model barriers to solids deposition ✪○<br>– use for development of fouling inhibitors<br><br>Life cycle cost analysis of R&D in materials ●<br><br>Model solid-liquid reactions | Study alternate alloy systems for high temperatures ✪✪●○<br><br>Develop new materials ✪<br>– wear/corrosion resistance<br>– separation materials<br>– specialty alloy<br>– electrolytic cells<br>– alternatives to asphalt<br>– high temp non-stick materials for high pressure<br><br>Explore alloys that develop adherent $SIO_2$ layer in service in high temperature environments ✪○<br>– shape stable electrodes<br>–<br><br>Resolve issues related to polymers use | Develop ceramic attachment interfaces<br><br>Develop casting methods for high temperature cast alloys ○ |

## Exhibit 4-3. Research Needs For Materials of Construction

(✪ = Top Priority; ● = High Priority; ○ = Medium Priority)
(♧= environment $=productivity ♻= safety ☼=energy)

| Time Frame | Science/ Knowledge/ Data$☼ | Control/ Inspection ♧♧♧♻♻♻♻♻♻♻♻ | Simulation/ Design/Prediction♧♧♧♧♧ $$$♻♻☼☼☼ | New/ Improved Materials ♧♧$$$$$☼☼☼☼☼☼☼ | Joining/ Fabrication ♧$♻ |
|---|---|---|---|---|---|
| **LONG** (>10 Years) | Investigate ways to prevent undesirable secondary phase formation | Develop NDE for fracture toughness ●● | Use fundamental computational chemistry/ MO-HF for corrosion and high temperature oxidation ● | | |
| **ONGOING** (All Periods) | Study degradation behavior in current environments ✪●<br>– kinetics<br>– initiation/ propagation<br><br>Study stress corrosion/ cracking phenomena ✪○ | Develop methods to detect *in situ* corrosion processes ✪ | Design user prototypes (simulate operating environment) ✪✪✪<br>– e.g. ceramic heat exchanger<br><br>Develop means to predict materials performance without empirical tests ✪●●●<br><br>Develop modeling tools for solids growth ✪<br>– surface chemistry<br><br>Reduce lead times to plant construction/ design through computer design | Develop longer life refractories that are field repairable and ductile ✪●○<br><br>Improve temperature and atmospheric stability of ceramic-metal-matrix composites ●<br><br>Develop new high temperature materials ○<br><br>Benchmark 2020 operating conditions as materials development goals<br><br>Explore surface modification and coatings for corrosive environments ○<br>– ION implantation | Investigate joining/fabrication techniques for ceramics and other brittle materials for chemical processing ✪○○● |

Notes: Symbols indicate that research will have significant impact on: the environment (♧); productivity ($); safety (♻); and energy consumption or efficiency (☼).

simulation of radiant heat transfer are important to the prediction of materials performance. Computational design tools are also needed to simulate the performance of brittle materials in chemical processes. These activities could build on the current knowledge base in the computational sciences and produce results in the near-term. Long-term on-going research is needed to apply computational chemistry methods to the simulation of corrosion and high-temperature oxidation conditions.

In the mid-term, modeling and predicting the life of new materials in high temperature environments is a top priority research need. This activity is critical to the increased use and acceptance of new materials in practical applications. Modeling of barriers to solids deposition is another top priority need. This research could lead to the development of fouling inhibitors that help eliminate fouling problems in heat exchangers and other equipment used throughout the CPI.

The development of a user/prototype simulation of operating environments is a top priority research need and an on-going activity over the near-, mid-, and long-term. Examples include prototypes of operating environments for ceramic heat exchangers and field testing apparatus. Predicting materials performance without empirical tests goes hand-in-hand with this activity, and is critical to promoting the use of new materials. Having this predictive capability would also enable significant progress toward eliminating materials failure and corrosion problems.

Proprietary issues are a major concern that must be addressed when developing data for new materials. Companies in the CPI consider the materials used in a given process as proprietary information. It is uncertain whether they would be willing to release the actual operating conditions within a process so that a realistic text matrix could be developed at an independent laboratory. The problem of how to shield proprietary data from general release will need to be resolved.

*New or Improved Materials*

The development of better, more cost-effective materials is the overall objective for new materials research. The study of alternate alloy systems for high-temperature applications is the highest priority in this area. Processes that occur at high temperatures have always been fraught with problems due to material constraints. New materials are also needed for: applications requiring increased wear and/or corrosion resistance, separation processes (e.g., innovative membranes), specialty alloys, high temperature non-stick materials, and materials for high pressure applications. Another area of interest is the additional investigation of alloys that develop an adherent silicon oxide layer while in service in high temperature environments (some research has already been done in this area in the steel industry).

On-going research programs are needed to develop refractories with longer life that are ductile and repairable in the field. Other important activities that may span the near- to the long-term include improving the stability of ceramic-metal-matrix composites, and exploring surface modification and/or coatings for use in corrosive environments.

*Joining and Fabrication*

Developing ways to join and fabricate ceramics and other brittle materials is a top priority research need. Ceramics do not lend themselves well to traditional joining processes, but have great potential for use in high temperature environments and could potentially be important materials of construction. Finding better ways to successfully join ceramics could facilitate their use in a wider range of high-temperature equipment.

*Non-R&D Actions*

Several supportive activities are needed to promote cooperation and communication between the materials research community and end-users. These include identification of outreach mechanisms to increase the transfer of information about research results and new material applications. A priority activity would be to foster increased collaboration for field testing of new materials and prototype equipment. Both these activities would serve to increase communication and interaction between the research and user communities, and would facilitate the optimum design of materials and equipment for specific applications.

## 4.4 Research Pathways

Exhibit 4-4 illustrates the connection between priority research activities and industry opportunities. For example, joining and fabrication techniques must be developed concurrently (as well as sequentially) along with new high temperature materials to enable their use in practical applications. Control and inspection methods will be needed to enable effective monitoring of new equipment. Research in basic science, data acquisition, and development of computational techniques will support all other activities in materials technology. Modeling tools will be needed to aid in the design process for high temperature materials (and other materials) so that the performance of these materials can be predicted with some reliability.

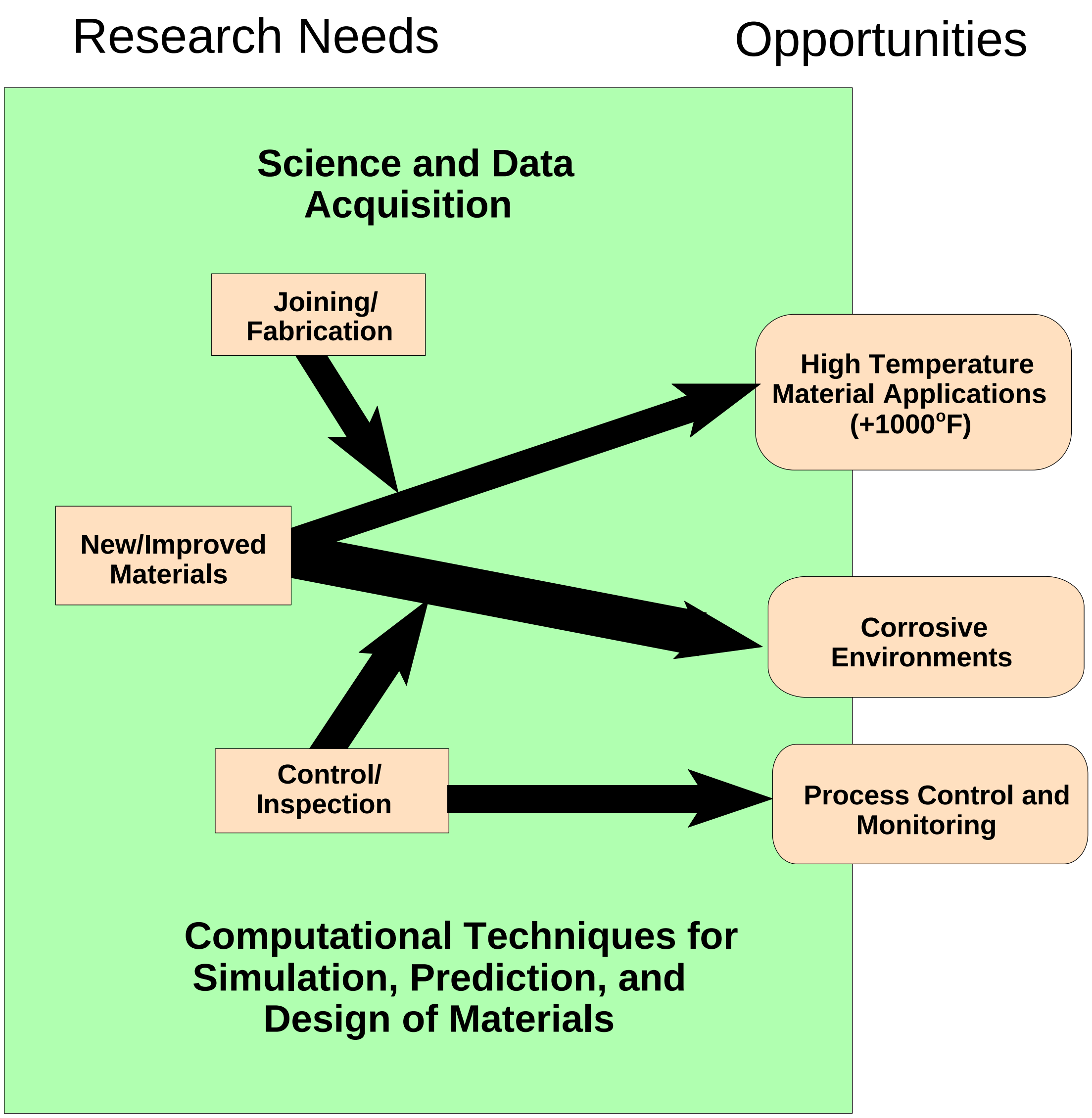


Exhibit 4-4. Links Between Priority Research Activities

# 5 Materials in Operations and Maintenance

## 5.1 Customer Needs and Opportunities for Materials in Operations and Maintenance

Materials have the ability to affect current and future operations and maintenance practices as well as creating entirely new methods of manufacturing. Exhibit 5-1 lists the opportunity areas within the chemical industry in which materials could make operations and maintenance more effective and less costly.

*Inspection and Monitoring*

One of the greatest potential areas for process improvement is to move inspection processes away from the "shut down" mode and make them non-intrusive and on-line. One opportunity is for measurements within closed vessels, which are currently difficult to obtain and frequently require a process shut down. Materials that can withstand extreme temperatures and pressures in vessel may be used as a basis for creating on-line sensing mechanisms that obviate the need for shut down. In general, opportunities for self-sensing systems for detecting fitness for service have significant potential for improving general operating and maintenance procedures.

A variety of inspection techniques could be used to facilitate the development of preventive maintenance programs and reduce equipment failure rates. These include non-destruction evaluation (NDE) techniques for a range of materials and situations (polymers, ceramics, ceramic/plastic composites), and inspection of vessel interiors, equipment cracks, and piping.

*Improved Materials and Coatings*

Improved corrosion resistant thermal spray coatings are an important area of opportunity. Metallic, ceramic, and plastic thermal spray coatings currently have limited corrosion resistance, and must either be reapplied periodically or treated chemically. Protective coatings could also be used to improve wear in mechanical processes. A substitute for asbestos, and the development of materials that resist corrosion under insulation are two areas where insulating procedures could be improved.

## Exhibit 5-1 Opportunities/Requirements For Materials in Operations and Maintenance

(◆ = Most Critical Problem Areas/Barriers)

| Repair/ Refurbish | Joints/ Joining | Standards & Codes | Inspection/ Monitoring | Improved Materials | Better Information | Assessment Tools |
|---|---|---|---|---|---|---|
| Improved repair methods for glass-lined steel<br><br>Methods of cleaning and preparation of process equipment<br><br>Ability to repair equip-ment with a minimum of special tools and/or training<br><br>More effective cleaning methods for polymer processing equipment<br><br>Flexible - use equipment (e.g. modular equipment)<br><br>Fitness of service for welded equipment | Reliable ways to seal-break and reseal equipment ◆<br><br>Highly reliable flange joints<br><br>Improved gasket design<br><br>High reliability, low service, long- life valves<br><br>Fool proof joints that minimize fugitive emissions | Codes and standards for maintenance of non-metallic equipment ◆<br><br>Availability of trained and certified inspectors and maint-enance personnel (non metallic construction) | Non-intrusive, on-line inspection ◆◆◆◆◆<br><br>Self-sensing systems for fitness for service ◆<br><br>Thermal insulation with wetness indicators ◆<br><br>NDE for<br>– polyethylene welds<br>– ceramics & plastic composites<br>– microwave (polymers)<br>– QC/QA of conductive coatings over conductive substrates (e.g., metal spray on steel)<br><br>Crack-evaluation (depth)<br><br>On-line measure-ment of degradation<br><br>Inspection of plastic lined steel pipe<br><br>*In-situ* monitoring of polymerization<br><br>Remote visual in-spection of vessel interiors<br><br>Field identification/ characterization of non-metallic materials<br><br>*In-situ* communications or embedded sensing and transmission<br><br>Enlarged applicability and reliability of corrosion probes | Better corrosion-resistant thermal spray coatings (metallic, ceramic, plastic) ◆◆◆<br><br>Improved methods of preparation of clad materials ◆<br><br>Protective coatings for mechanical processes<br><br>Asbestos substitute<br><br>Carbon-steel resistant to corrosion under insulation<br><br>Links between materials and their manu-facturing process<br><br>Tougher, robust ceramic equipment<br><br>Improved valve materials for monomers | Industry database for commonly used equip-ment ◆◆<br><br>Center for materials technology for common equipment<br><br>Data on generic contamina-tion of chemical environments and their effects on materials<br><br>Way to tag and identify all materials of construction | Tools to assess suitability of equipment for continued and alternate use ◆<br><br>Tools that relate material limits to pre-performance testing and fitness assessments ◆<br><br>Tools for *In-situ* characteri-zation of present and future MOCs ◆<br><br>Maximized global assess-ment tech-niques for entire vessels and piping systems |

*Better Information and Data*

An industry database of commonly used equipment and ways to tag and identify all materials of construction could potentially eliminate many problems and bottlenecks in a process plant. In general, a centralized database containing materials-related specifications and information for commonly used equipment in chemical processing would be highly useful for designing better operating and maintenance programs. This database could be fed by data obtained from “centers for materials technology” coordinated by universities or national laboratories, where information is collected on use of materials in practical operating environments. Information on many generic chemical environments and their effect on materials of use would also be of considerable use to specifying engineers. How to treat proprietary data on materials is an issue that would need to be addressed in developing this database.

*Assessment Tools*

Improved methods to assess whether equipment is suitable for continued use, should be scrapped, or should be salvaged and applied to an alternative use could have considerable impact on plant operating costs. It is also important to be able to relate the potential weaknesses in materials to performance and fitness in service. Having this capability could dramatically reduce the design phase for equipment and help predict impending equipment failure modes.

*Repair and Refurbishment*

More effective cleaning methods would be useful in a variety of applications — for process equipment in general and polymer processing equipment in particular. Better repair methods are needed to reduce maintenance costs for glass-lined steel equipment and welded vessels and tanks that contain welds that must be inspected and repaired. The ability to repair equipment in general could be improved by promoting more repairable equipment designs.

*Joints and Joining*

The highest priority opportunity area in joining techniques is the development of new reliable ways to seal-break and reseal equipment. Better seals and sealing designs would greatly reduce down-times and maintenance requirements for some equipment. Closely related is the opportunity to develop highly reliable flange joints, improved gasket designs, and longer-life low-service valves. Better joint designs are also needed to reduce or eliminate fugitive emissions from piping systems, seals, joints, pumps, vents, and other sources.

*Standards and Codes*

Developing codes and standards for the maintenance of non-metallic equipment is an important opportunity area and one that will be critical for the increased acceptance and use of advanced materials. Inspectors and maintenance personnel trained and certified in non-metallic equipment codes would be needed to support the implementation of these new codes. Improved construction codes would serve a similar function.

## 5.2 Technical and Non-Technical Barriers to Better Materials in Operations and Maintenance

The key barriers to developing and incorporating better materials in operations and maintenance are shown in Exhibit 5-2. The barriers are both technical and non-technical and cover a wide range of industry applications.

*Materials Design/Materials Processing*

One of the primary barriers to cost-effective materials design for chemical processing equipment is the lack of inexpensive, strong, corrosion resistant materials with low life cycle cost. The availability of these materials could enable considerable improvements in equipment failure and shut-down time while reducing equipment costs. A related barrier is the lack of cost-effective techniques for forming protective barriers that prevent or reduce corrosive action.

Lack of knowledge is a significantly limiting factor in several areas of materials design. There is limited definition and understanding of the sciences that model the behavior of corrosive and abrasive environments on surface layers applied to different substrates. Poorly developed theory in this area limits the accuracy of current models. Not enough is known about the effect of water on current and candidate insulation materials, which hinders the design and implementation process for new insulators.

The design of seal materials is limited in several ways. A critical barrier exists in the lack of sound engineering design knowledge for gasket materials as well as gasket design. There is also a lack of knowledge regarding the longevity and applicability for various sealers in differing types of operating conditions. Limited knowledge in this area contributes to poor design practices for seals and subsequently increased maintenance.

*Management, Policies, Infrastructure*

Although not strictly technological, management policies can represent a real obstacle to improvements in the materials field. A key barrier is the inability of industry to assess life-cycle costs on a consistent basis that includes material costs. There currently is no “cradle-to-grave” analysis of materials to help determine their applicability to certain applications and their actual lifetime cost. The result is a certain degree of trial and error in the selection of materials.

Other barriers in this category include limited funding for materials research, particularly as it pertains to operations and maintenance. This results partly from the lack of a long-term vision for materials that considers their important role in operations and maintenance (i.e., materials research is not considered a “hot” R&D topic).

*Information Synthesis and Transfer*

The key barrier in the area of information synthesis and transfer is that scientists and engineers currently cannot identify solutions based on the overwhelming amount of inconsistent, incomplete and not easily accessible data on materials. The primary problem is that there has been no concerted effort to organize the available materials information into a concise, usable interface. A contributing problem is the lack of definition for common equipment and associated materials specifications and performance. In some cases, such as failure analysis, the data needed to construct a usable database simply does not exist.

## Exhibit 5-2. Barriers to New Materials for Operations & Maintenance

(◆ = Most Critical Problem Areas/Barriers)

| Materials Design/ Materials Processing | Management, Policies, Infrastructure | Modeling/ Analysis | Information Synthesis and Transfer | Inspection/Monitoring | Supply Chain |
|---|---|---|---|---|---|
| Lack of an inexpensive strong, corrosive-resistant material with low life cycle cost ◆◆<br><br>Lack of cost-effective reliable techniques for forming protective barriers ◆<br><br>Lack of knowledge in gasket design ◆<br><br>Poor definition of sciences that model behavior of corrosive and abrasive environments on surface layers that are from different substrates ◆<br><br>Poor understanding of effect of $H_20$ on current and future candidate insulation materials<br><br>Unpredictable performance of thermal spray coatings<br><br>Coatings and linings have poor tolerance to non-optimum surface conditions<br><br>Lack of modularized insulation components<br><br>Lack of understanding of longevity and applicability of sealers in various types of conditions<br><br>Lack of standards and codes for certain materials | Inability of industry to look at life-cycle costs on a consistent basis ◆◆◆<br><br>Lack of leadership<br><br>Limited man - power and funding -- lack of long-term vision<br><br>Inability to effect cultural change in present NDE modification<br><br>Manipulation of company values based on Wall Street analyses | Inability to catalogue failure modes and effects for equipment reliability analysis<br><br>Lack of model for measurement of degradation of plastics<br><br>Lack of assessment of various NDE methods<br><br>Inability to categorize “upset conditions” that may safely be used to increase the applicability of steel | Inability to identify solutions due to poor data management and usability ◆◆◆<br><br>Lack of leadership to consolidate data bases/ technology centers ◆<br><br>Difficulty with putting information into a useful form<br><br>Inability to quickly access large amounts of data on materials<br><br>Lack of data for construc-ting effective failure-mode databases for materials and equipment | Lack of reliable cost-effective, on-line, in situ self-sensing methods ◆◆<br>– corrosion monitoring ◆<br>– wet insulation◆<br>– solid plastics/ plastic linings<br>– characterization of metals (high temperature)<br>– characterization of plastics at high temperature<br>– non-intrusive inspection<br><br>Limited NDE technology for non metallic and metallics-over-metallics ◆<br><br>Lack of means to consolidate materials characterization methods to make diagnostic tools ◆<br><br>Inability to measure environmental/ time effects on MOC for which predictive data is needed<br><br>Lack of ways to test for the relationship between NDE stimulus as it provides in-service condition of plastics | New or special technology is not available from OEMs ◆◆◆<br><br>Inability to take advantage of technical advances in other industries ◆◆<br><br>Failure to design and construct equipment for optimum inspection and cleaning methods ◆<br><br>High cost of designated process equipment that is self sensing |

*Inspection/Monitoring*
Reliable, cost-effective on-line *in-situ* self-sensing methods are limited. Of particular importance is the significant lack of self-sensing methods to monitor for corrosion, wet insulation, and residual stress. Sensing methods are also needed to inspect solid plastics, plastic linings, and metals and plastics at high temperatures. The inability to perform monitoring and inspection functions on these materials limits their acceptance in new applications and increases maintenance functions in existing applications.

Other barriers include limited non-destructive evaluation (NDE) technology for non-metallic materials, and the lack of means for consolidating materials characterization methods into useful diagnostic tools. Development of NDE for non-metallics and metallics-over-metallics would greatly facilitate the design, testing, and implementation of these materials in a wider range of applications.

*Supply Chain*
Innovations and new technology that incorporates unique materials is not readily available from original equipment manufacturers (OEMs). Many feel that they have to offer the lowest initial cost for equipment to be considered by end-users. There is a limited amount of prototype research in this field, and many of the methods that are currently in practice for materials selection in equipment are very old. Exacerbating this problem is the inability (or non-motivation) of OEMs to take advantage of and gather technical information from other industries that have implemented uniquely-designed equipment that utilizes advanced materials.

Another problem is that equipment from outside manufacturers is seldom designed and constructed for optimum inspection and cleaning, leading to less than effective maintenance practices and unnecessary equipment shut-downs. Closely related and contributing to this problem is the current high cost of process equipment that is specially designed to be self-sensing and easier to maintain.

*Modeling/Analysis*
There are a number of areas where models are lacking for basic analysis and prediction of materials and equipment performance. Key models are lacking for equipment failure modes and reliability analysis, as well as degradation mechanisms, particularly for plastics. These models are important for design engineers trying to test the reliability of new or existing equipment in different operating conditions.

Engineers also lack the means to assess the various techniques currently available for non-destructive evaluation (NDE) of materials, making it more difficult to chose the most appropriate option. Another practical barrier is the lack of information on the benefits of insulating versus the risk of corrosion, which creates a large degree of trial in error in operating practice and may lead to costly and unnecessary maintenance practices.

## 5.3 Research Needs for Better Materials in Operations and Maintenance

The research and development needed to overcome the barriers to improvements in materials for operations and maintenance are listed in Exhibit 5-3. This Exhibit displays the time frame for the research and indicates when meaningful results and process improvements can be expected. Symbols are used to indicate top, high and medium priority research. The relative impacts of research on safety, environment, energy and productivity are also illustrated for various research needs.

*Inspection and Monitoring*

In the near-term, a top priority research need is development of non-destructive methods to measure long-term metallurgical changes. Traditional strength testing for metals is destructive, and involves taking a metal sample and testing it to its point of failure as in tensile, compression, and impact testing. Another near-term research need is to develop cost-effective units that signal the moisture content of insulation. Moisture monitoring devices would help to optimize maintenance practices by indicating when insulation needs to be replaced or refurbished. In the mid-term, a top priority research need is development of methods for non-intrusive inspection of heat exchangers and storage tanks. These pieces of equipment are very prone to damage from corrosion in a process environment. Non-invasive monitoring could significantly decrease shut-down times and increase productivity. Another high priority research need is a system to inspect hidden details such as pipe supports. Failures in a plant frequently occur in places where inspection is difficult (pipe supports, gaskets, and insulation). Other priority research needs in this category include embedded sensors to detect water penetration and low hazard x-ray systems with image analysis capability.

*Information Transfer*

The establishment of technology centers for generic or typical processes could help scientists and engineers determine what materials and equipment would be optimum for their units and processes. Development of "how-to" guides for inspectors, users, and designers would educate individuals on the needs of their processes and lead to fewer run-time errors. Another priority research need is to develop the capability for analyzing new technology from other industries. Specifically methods are needed that will allow the identification of gaps and needs when transferring equipment from another industry to the chemical processing industry. This capability would greatly enhance the ability to take advantage of new materials developments outside of chemicals manufacture.

*Modeling and Analysis*

Research in this area can potentially have the greatest impact on materials for improved operations and maintenance. Accurate modeling can help eliminate much of the trial and error that is involved in pilot or bench-scale testing. Developing a uniform specification system model for materials is the most important research need in this category. This model could provide input for an industry database on CPI equipment. Predicting the overall cost and performance of equipment and materials is an important goal. This could be achieved in part through the use of a life cycle cost model for process equipment and piping systems. Other research needs in this area include a simple national system for classifying the taxonomy of equipment failure, and creation of a modular FRP equipment system to study FRP corrosion.

*Materials Design*

Much of the research needed in materials design involves ways to decrease corrosion in metals. A top priority is to develop more cost effective reliable techniques of covering steel with corrosion-resistant alloys. A supportive activity is to adopt knowledge obtained from developing corrosion-resistant steel and

## Exhibit 5-3 Research Needs for Materials in Operations & Maintenance

(✪ = Top Priority; ● = High Priority; ○ = Medium Priority)

(♧= environment $=productivity ☢= safety ☼=energy)

| Time Frame | Codes/Best Practices | Materials Design | Information Transfer | Inspection/ Monitoring | Modeling/ Analysis |
|---|---|---|---|---|---|
| **NEAR** (0-3 Years) | Develop design inspection and mainte-nance practices/codes for non-metallic materials ●○☢☢<br><br>Develop standard practices/codes for non-destructive testing and cleaning equipment $<br><br>Devise ways to extend the capability of 300 stainless steel in batch processes through operating or monitoring practices | Define economic benefits and improve systems for equipment (glass, ceramics, plastics) ○ | Establish technology centers for like processes ✪●○<br><br>Develop “How to” guides for inspectors, guides, users, designers to optimize use of materials ✪$☢<br><br>Devise methods to analyze technology from other industries to identify gaps and needs when trans-ferring to CPI ●$<br><br>Establish a center for NDE inspection methods for non-metallics ○☢<br><br>Develop data base and analysis tools that improve interpretation of main-tenance information | Devise non-destruct-methods to measure long term metallurgical changes ✪☢☢<br><br>Develop/remake cost-effective units that signal wet/dry insulation ●●○☼☼☼☼☼☼<br><br>Identify failure mechanics of FRP equipment ●○♧<br><br>Develop real-time 3-D ultrasonic image systems ●♧<br><br>Re-examine existing NDE technology with focus on non-intrusive applications<br><br>Establish database of standard internal TV inspection images of corrosion or damage to allow long distance problem solving | Develop a uniform specification system model (preparation for industry database for CPI equipment) ✪<br><br>Utilize life cycle cost model for process equipment and piping systems ●●●○○○$$$ ☼<br><br>Create modular system to study FRP corrosion ●●<br><br>Devise simple national system for classifying taxonomy of failure ●○☢☢<br><br>Develop overview of non intrusive inspection tools for better linkage without maintenance technologies $<br>– planning & scheduling<br><br>Devise methods of analyzing equipment supplier capability and linking it to specific goals (i.e. equipment reliability) $ |

## Exhibit 5-3 Research Needs for Materials in Operations & Maintenance

(✪ = Top Priority; ● = High Priority; ○ = Medium Priority)
(♧= environment $=productivity ☢= safety ☼=energy)

| Time Frame | Codes/Best Practices | Materials Design | Information Transfer | Inspection/ Monitoring | Modeling/ Analysis |
|---|---|---|---|---|---|
| **MID** (>3 - 10 Years) | | Develop more cost-effective reliable technique of covering steel with corrosion resistant alloys ✪●<br><br>Adopt knowledge from corrosion resistant steel and atmo-spheric steel techniques to produce CPI-resistant carbon steel ✪$<br><br>Determine the effects of composition on corrosion-resistant carbon steel ✪<br><br>Understand relationship between corrosion and wear and their effect on thermal spray coatings ○○<br><br>Develop and test inert insulation system for pressure system to prevent CUI ☼<br><br>Improve/ develop perfect organic barrier linings | | Devise methods for non-intrusive inspection of heat exchangers and storage tanks ✪✪✪♧♧♧$☼<br><br>Develop system to inspect hidden details (e.g., pipe supports) ✪●●○○♧♧☢☢☢<br><br>Develop low-hazard x-ray system with image analysis capability ✪☢<br><br>Design embedded sensors to detect $H_2O$ penetration ✪♧<br><br>Develop characterization techniques for non-metallics ●●<br><br>Develop crawlers or pigs for non-metallic pipe or lined steel ●○<br><br>Develop safe radar or sonar device to map tank interior and identify significant changes ○<br><br>Devise method to detect leaks in process equip-ment on-line in early stages ♧♧♧$$☢☢☼<br><br>Expand programs for testing suitability of ceramics $<br><br>Develop NDE for<br>- metallic-type coatings over conductive substrates (e.g., steel)<br>- FRP equipment<br><br>Devise units to signal upset conditions/loss of passivity<br><br>Develop economic field neutron radiography NDE | |

## Exhibit 5-3 Research Needs for Materials in Operations & Maintenance

(✪ = Top Priority; ● = High Priority; ○ = Medium Priority)
(♲= environment $=productivity ☢= safety ☼=energy)

| Time Frame | Codes/Best Practices | Materials Design | Information Transfer | Inspection/ Monitoring | Modeling/ Analysis |
|---|---|---|---|---|---|
| **LONG** (>10 Years) | Develop effective non-pollutant cleaning methods ♲♲☼ | | | | |
| **ONGOING** (All Periods) | Facilitate improved under standing between equipment cleaning vendors and $H_2O$ treat-ment vendors ☼☼<br><br>Develop ability to perform field maintenance under non-ideal con-ditions (e.g., relining, welding) | | Establish inter-industry and technology exchange service ●●$<br><br>Establish industry/gover nment funded organizations for advanced materials technology ● | Develop closure test program (e.g., flange) ✪○♲ | Define methods to estimate economical stakes for visionary results (e.g., improved thermal spray coatings) ○○ |

Notes: Symbols indicate that research will have significant impact on: the environment (♲); productivity ($); safety (☢); and energy consumption or efficiency (☼).

apply it to produce CUI- resistant carbon steel. An understanding of the effects of composition on corrosion-resistant carbon steel is also an important research need. In general, research is needed to help define the economic benefits of materials (e.g., glass, ceramics, plastics), and to then use this knowledge to help improve systems for equipment design.

*Codes and Best Practices*

This category includes ways to standardize the use and inspection of materials throughout industry. Examples include developing design inspection and maintenance codes for non-metallic materials, developing standardized practices for non-destructive testing and cleaning of equipment, and developing effective non-pollutant cleaning methods. Standardization makes both design and use of materials more reliable by providing consistent specifications that are accepted and recognized by all specifying engineers.

## 5.4 Research Pathways

Exhibit 5-4 reveals how some of the priority research needs and categories are related to each other. As new materials and joining practices are developed, appropriate techniques will be needed to inspect and maintain equipment. New methods for monitoring and control will provide better information on the performance of materials in situ, and will aid in the future development of codes that will standardize use of the new materials and enhance their acceptance in broader applications.

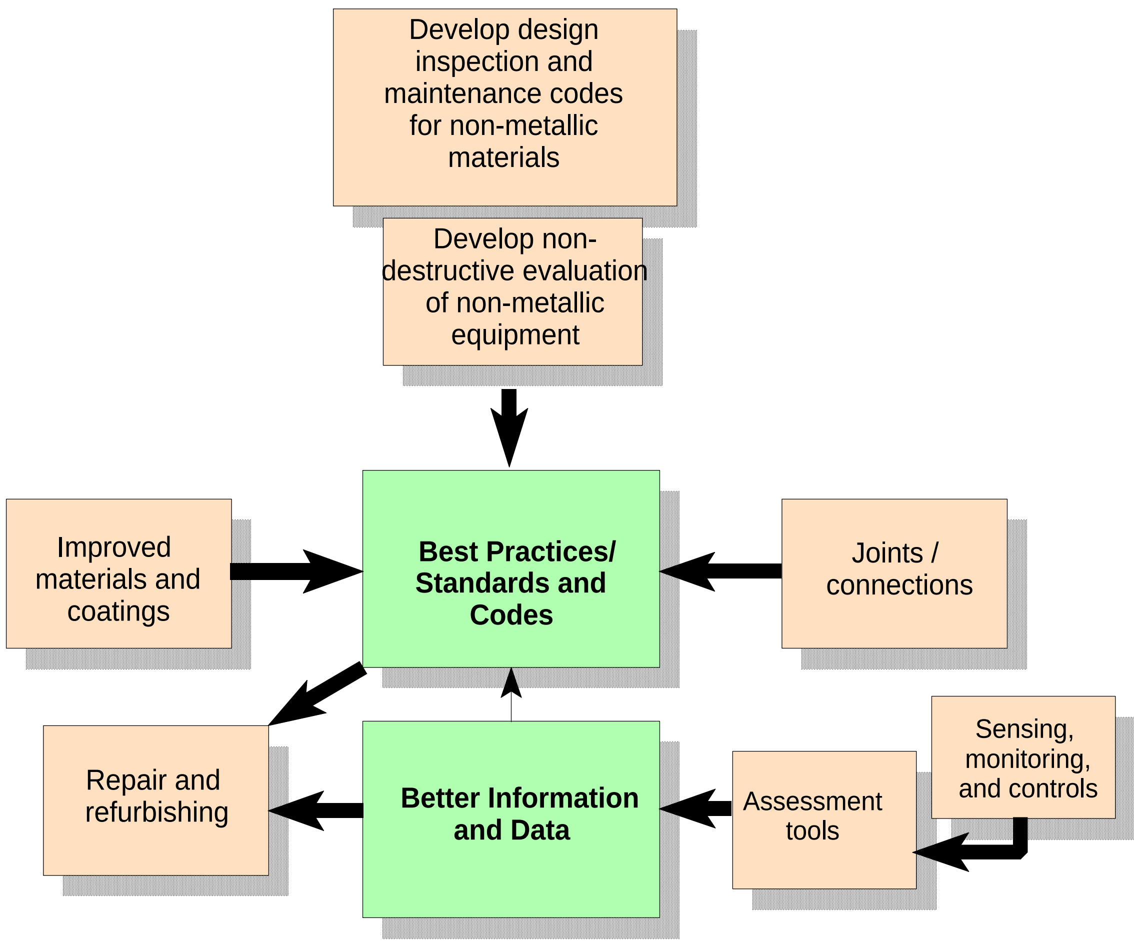


Exhibit 5-4. Links Between Research Priorities
for Materials in Operations and Maintenance

# 6 Next Steps

The development and use of new materials for construction of process equipment, and better performance in operation and maintenance is an important element in the continued health and world-competitive stature of the U.S. chemical industry. While many advances have been and continue to be made in materials development, there is consensus in the industrial community that better materials are still needed to meet the often severe requirements of chemical processing. These new materials could help increase productivity, reduce manufacturing costs, improve environmental performance, and lower the potential hazards to human health and safety posed by equipment failure.

## 6.1 The Road to Follow

The collaborative efforts that helped forge this roadmap have demonstrated that precompetitive research and development is needed to advance the development of materials of construction and to improve the performance of materials in operation and maintenance of chemical processing equipment. Exhibits 6-1 and 6-2 highlight the research that has been indicated as top priority by the chemical processing community. Areas of critical need are diverse, ranging from development of better inspection and monitoring techniques to the design of new and improved materials.

For effective resource leveraging, risk minimization, and providing a stable baseline for funding, precompetitive research should be cooperatively supported through the chemical industry, equipment manufacturers, and the Federal government. The development process should be directed by technology end-users.

Through research in high priority areas, progress can be made toward the major goals reflected in this roadmap: reduced capital costs and energy consumption, increased asset productivity, greater environmental protection, and a safe operating environment in the chemical processing industries.

## Exhibit 6-1. Priority Research in Materials of Construction for the CPI

| Science/Knowledge/Data Acquisition | Control/Inspection Techniques | Simulation/Design and Prediction | New/Improved Materials | Joining/Fabrication |
|---|---|---|---|---|
| Establish user facility for acquisition of thermo-physical, kinetic and mechanical data<br><br>Study the metal dusting phenomenon<br><br>Develop data for materials reliability and performance for ceramics and composites<br><br>Study the degradation behavior of materials in currently-used environments (e.g., kinetics, initiation/propagation mechanisms) | Develop big-picture controls and global inspection techniques<br><br>Categorize failure mechanisms for polymers<br><br>Develop non-destructive evaluation techniques (NDE) for fracture toughness<br><br>Develop methods to detect *in situ* corrosion processes | Design user prototypes and simulate operating environments (e.g., ceramic heat exchangers)<br><br>Develop the means to predict materials performance without empirical tests<br><br>Model and predict the life of high temperature materials using a macro approach<br><br>Conduct studies in computational modeling (e.g., fluid dynamics, radiant heat transfer)<br><br>Model the barriers to solids deposition to aid in development of fouling inhibitors | Study alternate alloy systems for high temperatures<br><br>Develop longer-life refractories that are field repairable and ductile<br><br>Develop new materials with superior properties<br>- wear/corrosion resistance<br>- separation materials<br>- specialty alloys<br>- electrolytic cells<br>- high temperature non-stick materials for high pressure environments | Investigate joining/fabrication techniques for ceramics and other brittle materials<br><br>Explore joining methods for ODS alloys<br><br>Develop casting methods for high temperature cast alloys |

## Exhibit 6-2. Priority Research in Materials for Better Performance in Operations and Maintenance in the CPI

| Codes/Best Practices | Materials Design | Information Transfer | Inspection/Monitoring | Modeling/Analysis |
|---|---|---|---|---|
| Develop design inspection and maintenance practices/codes for non-metallic materials | Develop more cost-effective, reliable techniques for covering steel with corrosion-resistant alloys<br><br>Adopt knowledge from corrosion resistant steel and atmo-spheric steel techniques to produce CPI- resistant carbon steel<br><br>Determine the effects of composition on corrosion- resistant carbon steel | Establish technology centers for like processes<br><br>Develop “How to” guides for inspectors, guides, users, designers to optimize use of materials<br><br>Devise methods to analyze technology from other industries to identify gaps and needs when trans-ferring to CPI | Devise methods for non-intrusive inspection of heat exchangers and storage tanks<br><br>Develop systems to inspect hidden details in equipment and processes (e.g., pipe supports)<br><br>Devise non-destruct-methods to measure long term metallurgical changes<br><br>Develop/remake cost-effective units that signal wet/dry insulation | Utilize life cycle cost model for process equipment and piping systems<br><br>Develop a uniform specification system model (preparation for industry database for CPI equipment)<br><br>Create modular system to study FRP corrosion<br><br>Devise simple national system for classifying taxonomy of failure |